one side and re-mixed on the other side. Finally the mixed solution enters the observation chamber, indicated by the passage of light, and into the stop-syringe. Fig. 4 shows the plastic block in which the various parts are assembled.

Methods for testing stopped-flow mixers have been described (1, 8). One involves observation of optical absorption changes of acid-base indicators upon changing the pH in the mixing process. The protonation and deprotonation reaction of acid-base indicators are very fast and therefore, any absorbance change observed after flow stop is due to the kinetics of mixing and not of the chemical reaction (7). In tests of our mixing system, we observe less than 2% of the expected absorbance change to occur after flow stop. Another test method involves the extrapolation of absorbance versus time data from an observed first-order reaction back to the known initial absorbance at the point of mixing to obtain a measure of the dead time of the mixer. For our mixer this varies from 10 to 20 ms, though it may be reduced by increasing the flow rate of the reacting solutions above that used for this test (Fig. 5), which was about 7 ml/s (i.e., a maximal linear flow velocity of about 9 m/s).

This mixing method has been applied to the study of spontaneous and protein-catalyzed superoxide dismutation (9, 10) and the reactions of O_2^- with Fe (II) and Fe(III) chelated by ethylenediaminetetraacetic acid (EDTA) (11).

This work was supported in part by U. S. Public Health Service grant 21519 and a National Science Foundation Graduate Fellowship to G. J. McC.

REFERENCES

1. GIBSON, Q. H. 1969. *Methods Enzymol.* Vol. 16.
2. BORS, W., M. SARAN, E. LENGFELDER, R. SPOTTL, and C. MICHEL. 1974. *Curr. Top. Radiat. Res.* **9**: 247.
3. VALENTINE, J. S., and A. B. CURTIS. 1975. *J. Am. Chem. Soc.* **97**:224.
4. MARKLUND, S. 1976. *J. Biol. Chem.* **251**:7504.
5. FOX, M. F. 1975. *J. Chem. Soc. Faraday Trans. I.* **21**:1407.
6. BERGER, R. L., B. BALKO, and H. F. CHAPMAN. 1968. *Rev. Sci. Instrum.* **39**:493–498.
7. BRODKEY, R. S., editor. 1975. Turbulence in Mixing Operations. Academic Press, Inc., New York.
8. BALLOU, D. 1971. Ph. D. Dissertation, University of Michigan, University Microfilms, Ann Arbor, Mich.
9. MCCLUNE, G. J., and J. A. FEE. 1976. *Fed. Eur. Biochem. Soc. (FEBS) Lett.* **67**:294.
10. FEE, J. A., and G. J. MCCLUNE. 1978. Mechanisms of Oxidizing enzymes. Proceedings of an International Symposium on the Mechanisms of Ozidizing Enzymes, La Paz, Baja, Mexico, Dec. 5–7, 1977. T. P. Singer and P. N. Ondarza, editors. Elsevier-North Holland, Amsterdam. 273.
11. MCCLUNE, G. J., J. A. FEE, G. A. M. MCCLUSKEY, and J. T. GROVES. 1977. *J. Am. Chem. Soc.* **99**: 5229.

FLUID MECHANICS OF RAPID MIXING

JEROME H. MILGRAM, *Massachusetts Institute of Technology, Cambridge, Massachusetts 02139 U. S. A.*

Theoretical and experimental studies and analysis of rapid mixing processes will result in an increased understanding of the mechanics that may lead to the development of

improved devices. For example, suppose the order of magnitude of the mixing time that can be achieved is examined. The diffusion length l_d is given by $l_d \sim \sqrt{Dt}$ where D is the diffusion coefficient and t is the mixing time. The length scale, η, of the microscale eddies is given by $\eta \sim (\nu^3/\epsilon)^{1/4}$, where ν is the kinematic viscosity of the fluid and ϵ is the rate of dissipation of the energy of the turbulence (per unit time and mass). An efficient mixing apparatus will dissipate a substantial fraction of the turbulence energy in the mixing time, so $\epsilon \sim E/t$, where E is the initial energy of the turbulence. Sufficient mixing requires that the order of magnitude of η be at least as small as that of l_d, so the minimum order of magnitude of the mixing time is found by equating η to l_d: $t \sim \nu^3/D^2E$. We can write $E = u^2$, where u is the characteristic speed of the turbulence, so that $t \sim \nu^3/D^2u^2$. Now suppose we choose typical values of $D = 10^{-5}$ cm^2/s and $\nu = 10^{-2}$ cm^2/s. Then, $t \sim 10^4/u^2$ cm^2/s. Thus, for a characteristic turbulence flow speed, u, of 10 m/s, $t \simeq 10^{-2}$ s, and for $u = 100$ m/s, $t \simeq 10^{-4}$ s.

This simple analysis yields an important relationship between the order of magnitude of the mixing time and the flow speed. It can be used to compare the mixing times for a given apparatus run at different speeds or with materials of different kinematic viscosities or diffusion coefficients. Similar analyses can be used for obtaining limits on orders of magnitude of other important factors, such as cavitation and pressure forces. These results are helpful in relating gross design features to performance. However, such analyses do not provide a detailed comparison of various mixer types or yield much information on design details. Those matters are best studied with experiments. Most flow apparatuses are too small to allow convenient use of hot film anemometry, the most useful technique for measuring turbulence in liquids. However, it is possible to properly scale both Reynolds and cavitation numbers in scaled-up apparatuses and make the turbulence measurements in them.

For our experiments, a Johnson Research Foundation Model B mixing apparatus design is scaled up by a factor of six, giving a cross-sectional size for the observation section of 6 cm × 6 cm. To scale the Reynolds number, the flow speed is reduced by a factor of six. Then to scale the cavitation number simultaneously, the pressure (referenced to the vapor pressure) is reduced by a factor of 36. These scaled parameters result in flow speeds and pressures easily attained in the scaled-up apparatus. Most of the measurements of the flow field, including mixing effects, are made with hot film anemometry. However, the device is also suitable for measurements by laser anemometry, and these are being contemplated for those functions of the turbulence that can be measured by single-component anemometry. The degree of mixing is being measured by colorimetry on a pH-sensitive indicator.

The author of this paper did not attend the actual Discussion. The present text was submitted and circulated to participants before the meeting.